ANALYTICAL THERMAL MODEL VALIDATION FOR CASSINI RADIOISOTOPE THERMOELECTRIC GENERATOR[1]*

by

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ABSTRACT

The Cassini spacecraft is being developed for a mission to investigate Saturn and its rings, satellites and magnetosphere. The spacecraft will be powered by three Radioisotope Thermoelectric Generators (RTG, see Figure J), The utilization of the RTG waste heat as a major heat source for thermal control of the Propulsion Module Subsystem (PM S) is a new concept (see 1 'igure 2) that has never been applied before, neither for (is] ileo nor for Ulysses. '1 'hermal development test has been conducted to demonstrate that the RT '(is can provide a significant part of the heat necessary to warm the PMS, and that the RTG end dome temperature is critical in determining the amount of heat entering the PMS cavity (a large MLI blanket drapes over the propellant tanks forming the cavity). However, anal ysis indicated that there was a large discrepancy between the flight RTG thermal analytical model predictions and the test results based on an misting RTG simulator hardware, especial] y with regard to the end dome temperatures. This raised questions concerning the adequacy of the existing simulators as well as the analytical model.

This paper addresses the adequacy of the analytical model. '1 'he model was developed a number of years ago by GE under a contract with JPL. It deals with the complex design and thermal behavior of the RTG that are to some degree reflected in the schematics of Figure 3, The model in its reduced form has a node map as shown in Figure 4. The model has been relied upon as the sole guide with its analytical predictions for interpreting the RTG thermal behavior. However, upon reviewing flight data from Galileo and Ul ysses (missions to explore Jupiter and the sun, respectivel y), as weJJ as past gwuncl-test data, it was discovered that there had only been one validation case performed for the model, and that it was dcmc without due attention to the end dome temperatures (because they were not a matter of concern for those missions). Uncertainty with regard to the predicted end dome temperat ures, therefore, appeared great and needed to be minimized.

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Model Modification and Validation Using the Engineering Unit Data

The mode] was correlated once in 1988 by GE with the only set of' vacuum test data available from the Engineering Unit (an electric simulator). However, as a close scrutiny reveals, the previously correlated model (due, to focus on power performance) under-predicts the end dome temperature by 10°C, over-predicts the flange temperature by 9°C, and over-predicts the mid-shell temperature by 14°C, as compared with the test data. The model was found deficient in two important areas, i.e., the underestimate of radiative coupling, between the end dome and the heat source support assembly, and the absence of radiative coupling between the dome/shell flanges and space. Each deficiency, when corrected, led to a substantial temperature change. Other modifications, less significant in comparison, were also made. Figures 5-13 show results of each successive step of mollification. The final validated model brings the end dome and flange temperature predictions to within 2°C of the test data, as shown in Figure 14, and results in a doubling of the radiative heat transfer from the RTG heat source support assemblies to the end domes,

More significantly, when the RTG is coupled to the interface ring, the support box and the spacecraft central body, as in the integrated Cassini configuration, the combined model predicts an inboard end dome temperature of 194°C after the validation, as opposed to 169°C before. This 25°C increase in the end dome temperature has a considerable impact cm the amount of RTG heat entering the PMS cavity,

Validation with the F-2 RTG Thermal Vacuum Qualification Data

Since GE's Engineering Unit was an electric simulator and not a nuclear-fueled flight unit, it was highly desirable to acquire vacuum data from a fueled flight unit for further validation of the analytical model. Upon JPL's request, an effort was made by DOE's Mound Laboratory (with assistance from Lockheed Martin personnel) to obtain end dome and shell temperature measurements during the thermal vacuum qualification test of the fueled flight unit F-2. The shell temperature measurements were obtained with flight temperature transducers that are in place on the RTG while the end dome temperature measurement (being an afterthought) was obtained by using an IR probe inside the vacuum chamber, and the results are shown in Figure 15. The IR probe was calibrated using an oil-bath setup as well as a hot plate, the latter arrangement being shown in Figure 16. Both calibration approaches yielded a consistent correction factor of 22°C at the temperature reading of around 200°C. Applying this correction factor to the lower curve of Figure 15, the end dome temperature is determined to be 208°C. The shell temperature at the "RTD" location (approximately 7 in. from the dome flange), as shown in Figure 15 and with no correction necessary, is 244°C. The F-2 was running with a net thermal power of 4120 W, and the sink (or chamber shroud) temperature was 27°C.

Prediction using the analytical mode] for the same operating conditions yielded an end dome temperature of 210°C (cf. F-2 data of 208°C) and a shell temperature at the "RTD" location of approximately 240°C (cf. F-2 data of 244°C). These are rather satisfactory comparisons, and the validity of the RTG analytical model is thus established.

The Cassini Integrated Configuration with the RTG Simulators

The fueled RTGs cannot be used in the Cassini spacecraft system-level solar thermal vacuum test, and suitable simulators must be used instead. The adequacy of the simulators, and the uncertainty they introduced, are important subjects whose discussion requires a separate treatment (see Figure 17 for a test arrangement involving, a simulator and the surrounding, components). The validated flight RTG analytical model discussed in this paper is relied upon heavily to provide guidance in assessing those issues.

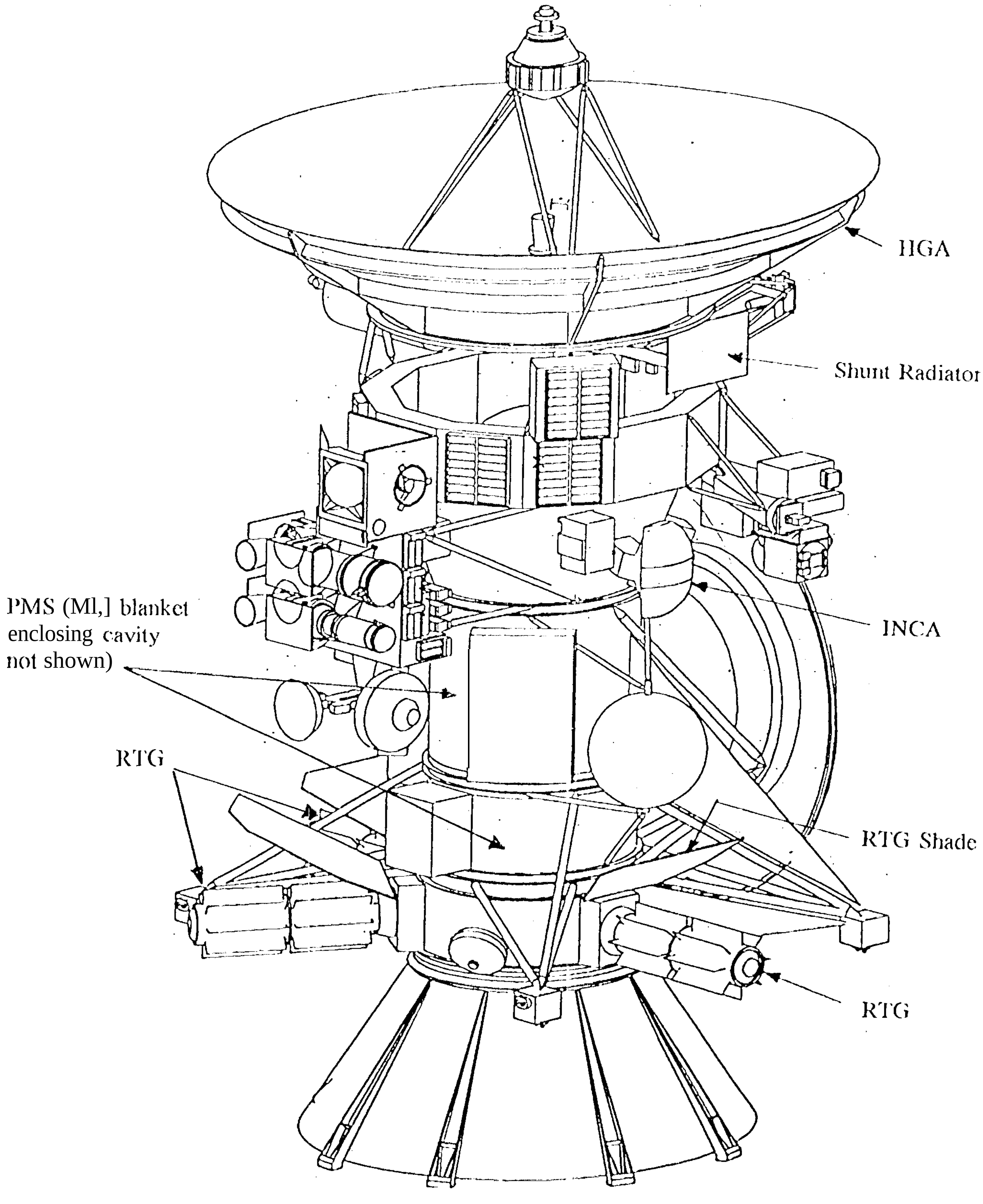


Fig. 1 The Cassini Spacecraft and the RTGs

JPL

RTG Waste Heat Concept

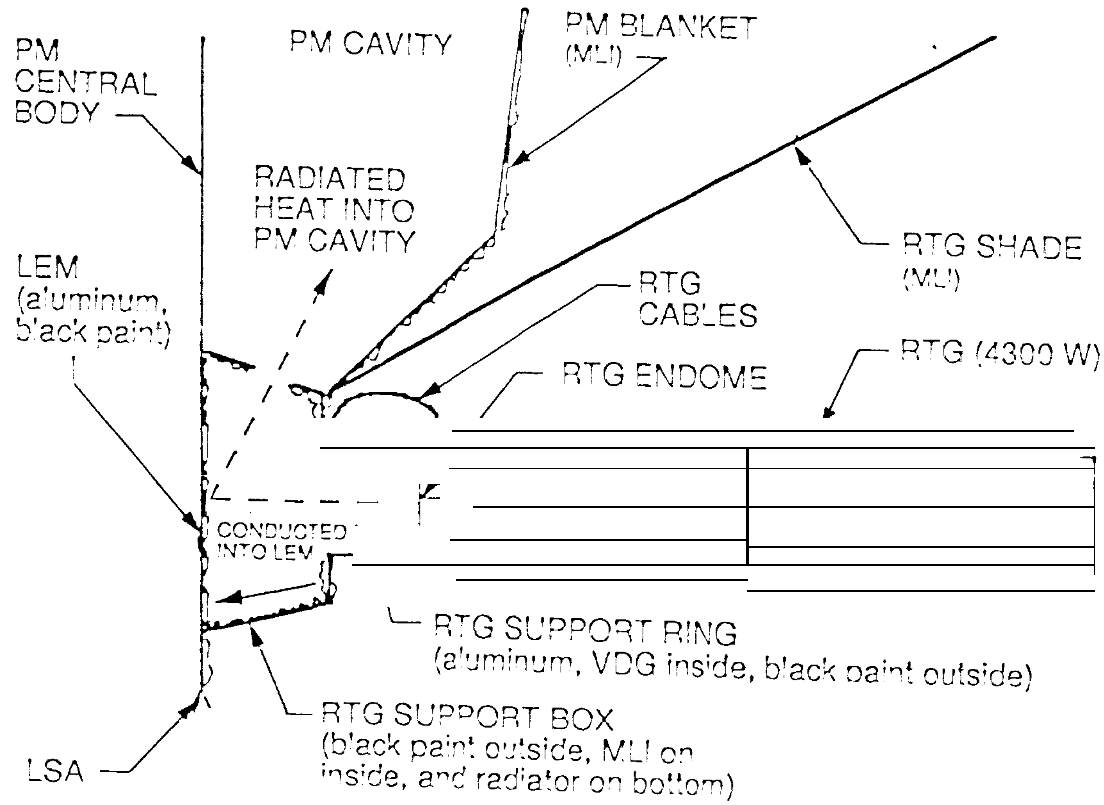
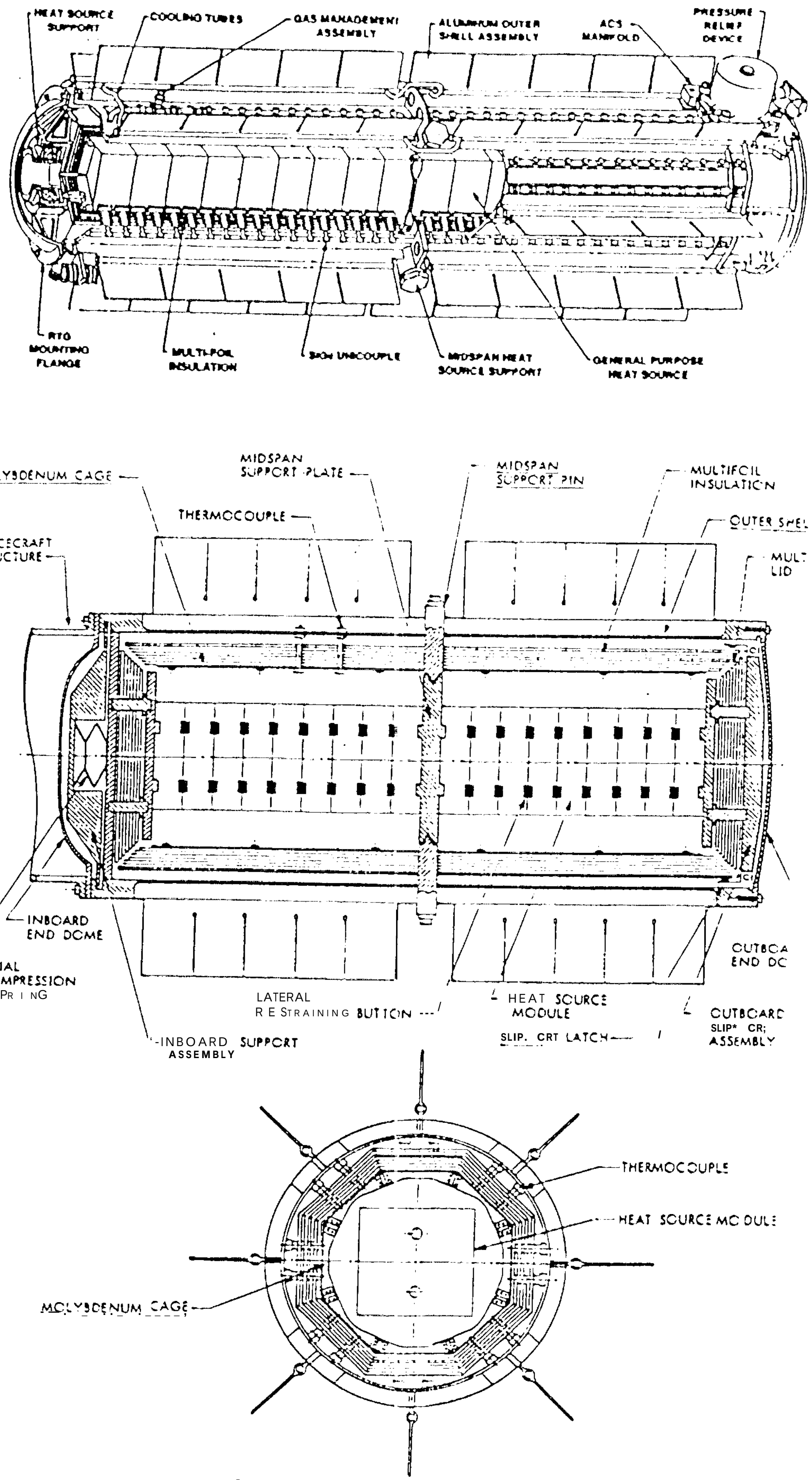


Fig. 2 Heat Radiated and Conducted From the RTG into the PMS Cavity



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Fig, 2 Schematic of RTG Elements

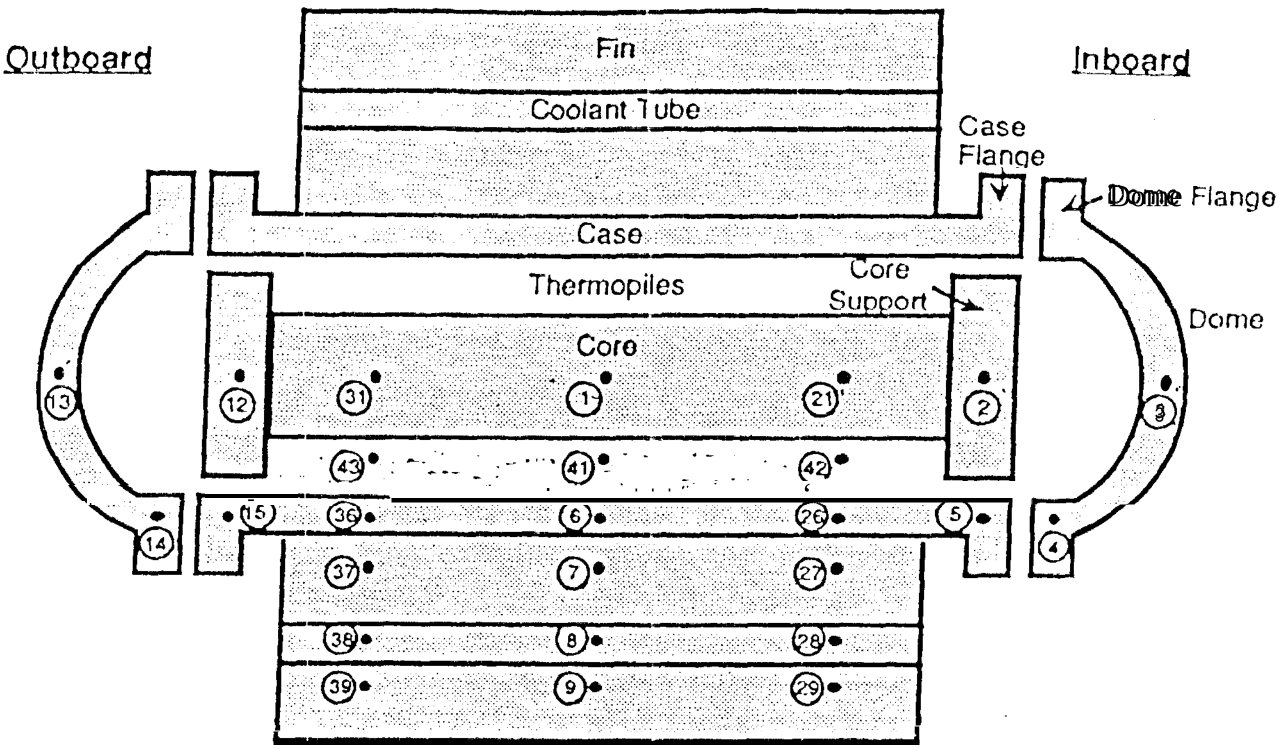

Figure 4 - RTG Thermal Model Node Map

NOTE: The temperatures presented in Figs. ~~8-16~~ 5-13 are in °C and correspond to nodes as defined in the thermal model node map (Fig. 4)

OUTBOARD						INBOARD
205.47	752.17	999.96	1076.68	1004.45	774.35	204.50
		616.86	673.95	619.03		
217.42	220.80	233.75	271.22	233.60	218.51	215.42
		218.61	251.33	218.48		
		210.91	241.39	210.79		
		180.05	201.66	179.97		

Fig. ~~8~~ 5 Results of Run # 1: Duplicating the "Baseline Predictions"

OUTBOARD						INBOARD
190.21	743.99	995.36	1075.60	1000.00	766.73	189.45
		612.01	673.20	614.29		
197.57	201.75	228.66	270.81	228.58	199.73	195.85
		214.16	250.96	214.09		
		206.77	241.03	206.70		
		177.09	201.38	177.04		

Fig. ~~9~~ 6 Results of Run # 2: Adding Flange-to-Space Radiative Coupling

OUTBOARD						INBOARD
164.79	975.17	1046.87	1085.70	1056.67	1022.92	161.89
		638.81	679.03	643.69		
183.56	190.67	230.76	272.35	230.71	186.85	180.00
		216.02	252.31	215.97		
		208.50	242.29	208.46		
		178.36	202.28	178.33		

Fig. ~~10~~ 7 Results of Run #3: Deleting Lumped Conductance Between End Domes and Heat Source Support Assemblies

OUTBOARD						INBOARD
167.79	974.64	1046.46	1085.61	1056.31	1022.50	164.79
		638.35	678.96	643,26		
187.25	188.72	230.24	272.32	230.22	184.97	183.56
		215.56	252.28	215.54		
		208.08	242.26	208.06		
		178.05	202.25	178.04		

Fig. ~~11~~ 8 Results of Run #4: Increasing Contact Conductance Between the Shell Flange and Dome Flange

OUTBOARD						INBOARD
216.49	488.40	938.19	1064.52	938.99	492.42	216.81
		582.02	666.79	582.39		
212.01	212.24	225.85	269.06	225.79	211.67	211.49
		211.68	249.42	211.63		
		204.45	239.60	204.40		
		175.40	200.35	175.36		

Fig. ~~12~~ 9 Results of Run #5: Adding Radiative Coupling Between End Domes and Heat Source Support Assemblies

OUTBOARD						INBOARD
211.68	471.24	950.35	1066.80	951.07	475.38	212.02
		588.36	668.11	588.68		
209.31	209.65	226.36	269.42	226.30	209.14	208.85
		212.14	249.74	212.08		
		204.87	239.90	204.82		
		175.71	200.56	175.67		

Fig. ~~13~~ 10 Results of Run #/6: Reducing Conductances Between Nodes 2 and 21, and Nodes 12 and 31

OUTBOARD						INBOARD
210.80	470.22	947.05	1058.60	947.75	474.36	211.08
		585.99	659.44	586.30		
208.33	208.65	224.94	260.27	224.86	208.07	207.79
		210.79	241.76	210.71		
		203.57	232.47	203.50		
		174.60	195.29	174.55		

Fig ~~14~~ 11 Results of Run #7: Including Radiative Coupling Between the Mid-ring and Space

OUTBOARD						INBOARD
209.74	469.44	944.90	1055.32	945.61	473.60	210.04
		583.92	656.05	584.24		
207.04	207.35	222.94	256.78	222.87	206.80	206.54
		210.06	240,20	209.99		
		203.47	231.85	203.41		
		177.25	198.78	17?.21		

Fig. ~~15~~ 12 Results of Run #8: Adding Shell-to-Fin Radiative Coupling

OUTBOARD						INBOARD
212.01	442.34	939.60	1054.36	940.17	445.71	212.31
		581.15	655.51	581.41		
208.16	208.41	222.71	256.65	222.64	207.94	207.73
		209.85	240.10	209.79		
		203.27	231.75	203.22		
		177.10	198.70	177.06		

Fig. ~~16~~ 13 Results of Run #9: Fine-tuning Radiative Coupling Between End Domes and Heat Source Support Assemblies

-- "Validated Model Predictions"

Note: All temperatures are in °C. Predictions by the validated 26-node model are bracketed <...>. All other temperatures are test data from the Engineering Unit.

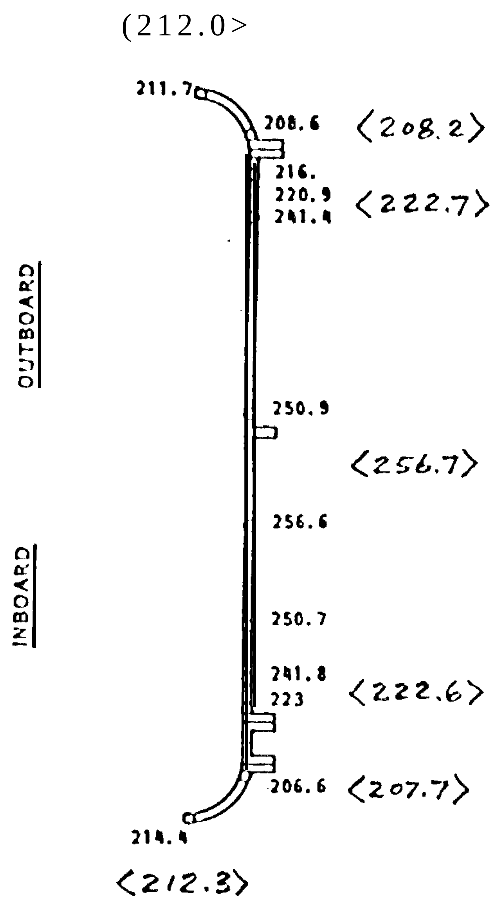

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Fig. 17 RTG Engineering Unit Test Data vs. Predictions by the Validated 26-Node Model

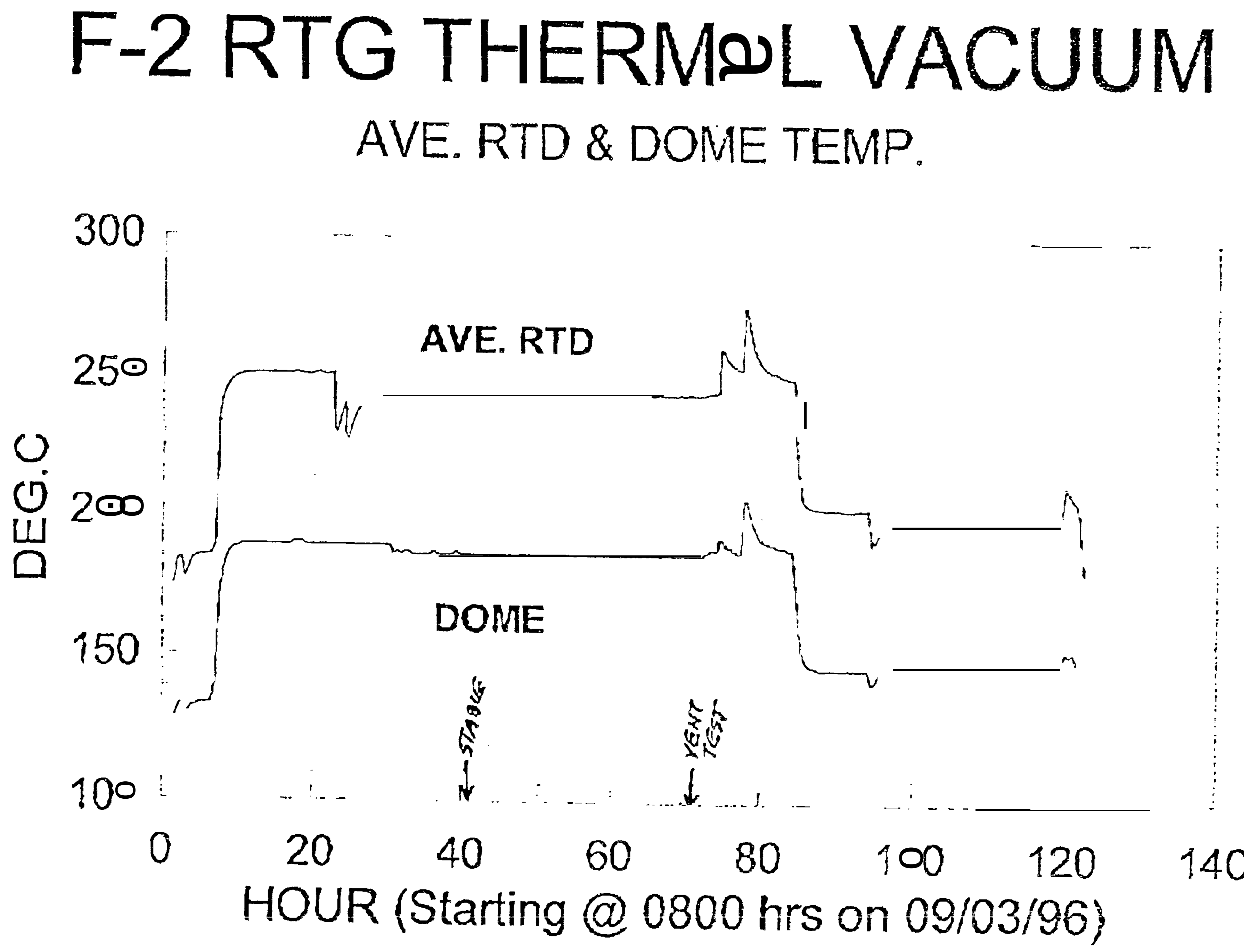

Fig. 15 RTG temperature measurements during F-2 thermal vacuum qualification test

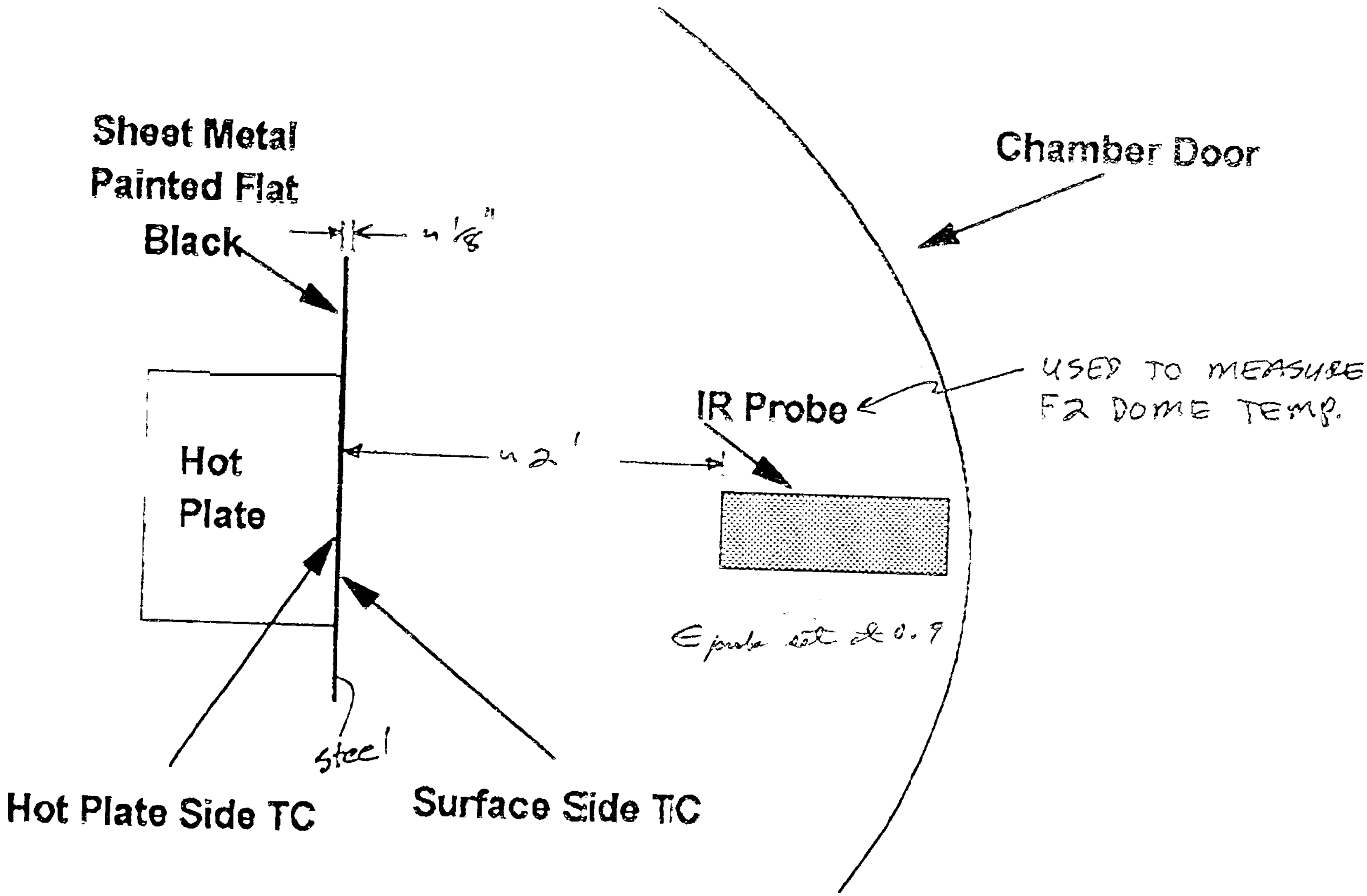

Fig. 16 One of the IR probe calibration setups

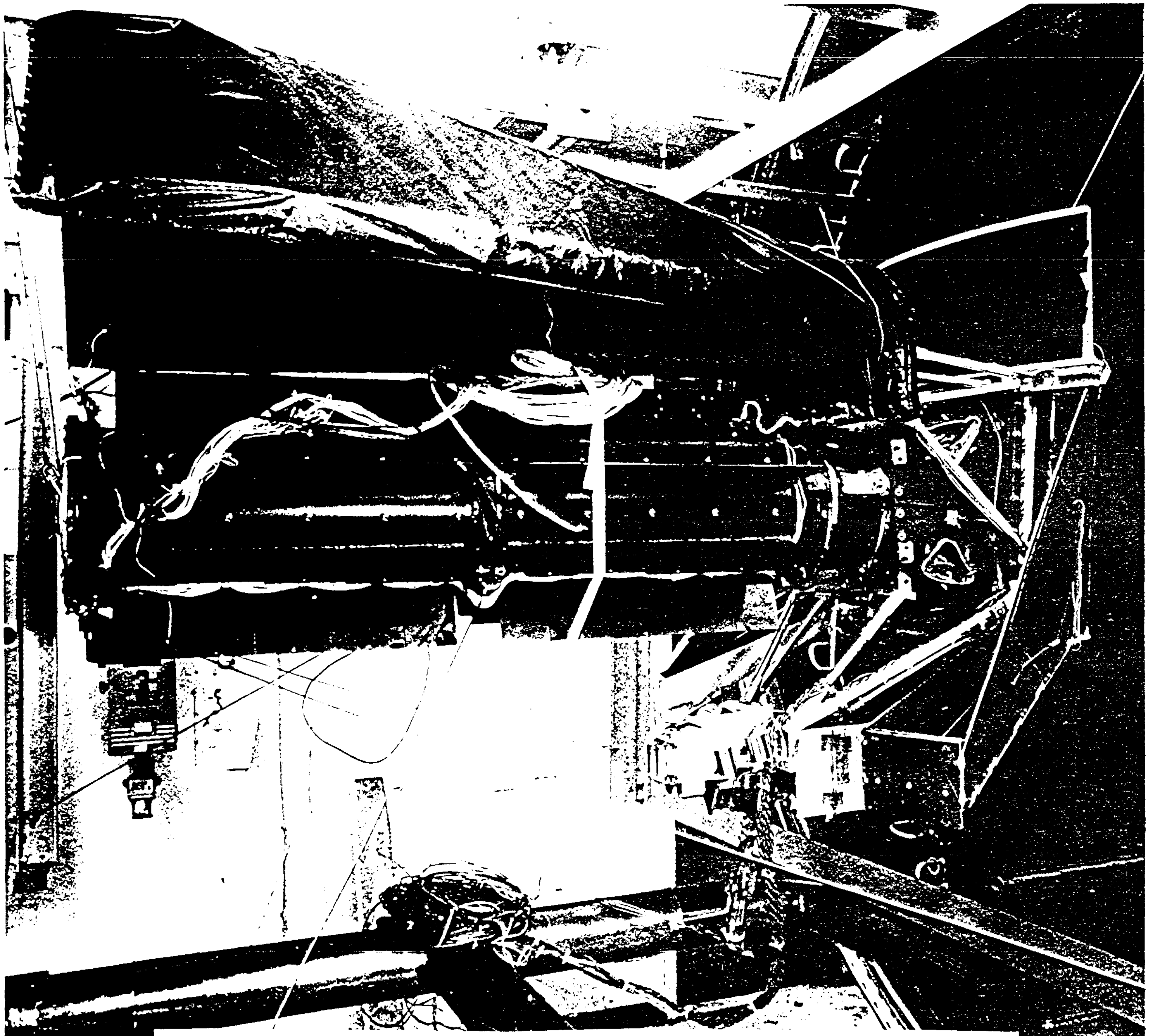

Fig. 17 A test setup involving a Cassini RTG simulator and its surrounding components